Stiction reduction processes for surface micromachines

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We present a review of surface micromachining technology with an emphasis on polycrystalline silicon (polysilicon) microstructures. The problems of release-related and in-use stiction are then introduced along with a brief review of various approaches developed for reducing them. These include surface roughening and chemical modification of the silicon surfaces. The constraints that post-release back-end processes such as assembly and packaging place on surface treatments are described in general. Finally, we briefly outline some of the important scientific and technological issues that remain to be clarified in stiction phenomena in micromechanical structures.

Keywords: surface micromachining, MEMS, stiction, adhesion

1. Introduction

Surface micromachining is a process for making micromechanical structures from deposited thin films. By selectively etching sacrificial layers from a stack of patterned thin films, micromechanical structures such as suspended plates, bearings, gears, and hinges are released from the substrate [1,2]. This process is a primary technology for silicon micro-electromechanical systems (MEMS) and is now used in manufacturing accelerometers for air-bag deployment [3] and digital micromirror devices for projection displays [4]. Polysilicon surface micromachining has become standardized to the point where it is available through foundries [5,6].

Surface microstructures have lateral dimensions of 50–500 μm, with thicknesses of 0.1–2.5 μm and are offset 0.1–2 μm from the substrate. Given their large surface area-to-volume ratio, they are particularly vulnerable to adhesion to the substrate or adjacent microstructures during the release process or later, during use. This phenomenon is more generally called stiction since one is often dealing with a restoring force in these microdevices that has a tangential as well as a vertical component. This subject has recently been reviewed [7]. Since microactuators have surfaces in normal or sliding contact, friction and wear are important issues. Various surface coatings have been investigated to reduce stiction and friction in micromechanical structures. These coatings must be compatible with the surface microstructure fabrication and release process. In addition, surface coatings must be compatible with the "back-end" processes of wafer dicing, die attachment, and final hermetic encapsulation.

This paper provides a perspective on stiction processes for surface micromachines, with an emphasis on polycrystalline silicon (polysilicon) as a microstructural material. After a review of polysilicon surface micromachining, we briefly describe the various approaches to eliminating stiction during drying following the release step. The constraints imposed by the thermal cycles of back-end processes are outlined, which are a major consideration in developing coatings to reduce "in-use" stiction or friction in packaged MEMS. Finally, we outline some of the important scientific and technological issues that remain to be clarified in stiction.

2. Surface micromachining technology

Fig. 1 illustrates in a series of cross sections the basic steps in a surface micromachining process [8]. First, the substrate is typically coated with an isolation layer (fig. 1a) that protects it during subsequent etching steps. A sacrificial layer is then deposited on the substrate and patterned. For simplicity, fig. 1b shows that the opening of the sacrificial layer is terminated on the isolation layer. The microstructural thin film is then deposited and etched (fig. 1c). Selective etching of the sacrificial layer creates the free-standing micromechanical cantilever beam shown in cross section in fig. 1d. The technique can be extended to make multiple-layer microstructures.

An important example of surface micromachining is polysilicon microstructures. In this case, the sacrificial layer is an oxide film, the isolation layer is typically silicon nitride, and the structural layer is polysilicon deposited by low-pressure chemical vapor deposition (LPCVD). The oxide film is etched by hydrofluoric acid (HF), which etches silicon nitride relatively slowly and usually has a negligible effect on polysilicon. Fig. 2 is a SEM of a portion of the suspension and interdigitated

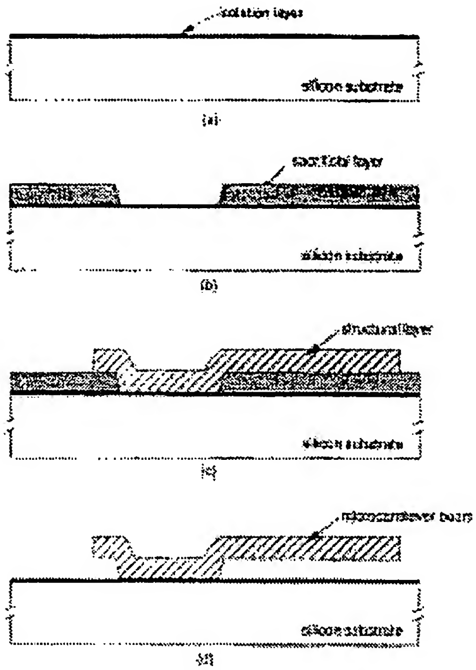


Fig. 1. Schematics of basic steps employed in a surface micromachining fabrication process.

sense and force feedback electrodes of a surface micromachined accelerometer, which is fabricated from a 2 μm thick polysilicon structural layer that is suspended 1.6 μm above the substrate [9]. The associated detection, control, and signal-processing electronics are cofabricated with the polysilicon microstructure on the same silicon chip.

Attempts to fabricate surface microstructures using the basic process sequence in fig. 1 often encounter microstructure adhesion to the substrate after drying from the final rinsing step, following sacrificial layer etching. Polysilicon microstructures can be passivated with 20–30 Å of SiO_2, which can be formed by exposure to an oxidant such as H_2O_2 [10] after the release etch. The oxidized polysilicon surface is hydrophilic, with a water contact angle in the range 0–30°. Capillary forces generated by the concave meniscus formed between the structure and substrate are sufficiently strong to collapse a typical suspended microstructure to the substrate [11]. Permanent adhesion can occur by means of solid bridging of dissolved silica residues from the rinse solution. This phenomenon is called "release-related stiction".

Surface microstructures also suffer from post-release stiction to the substrate or to adjacent microstructures, due to intentional or unintentional inputs. The permanent adhesion arises from the large interfacial forces in comparison to the restoring force of the deflected suspension. Friction and wear in surface micromachined

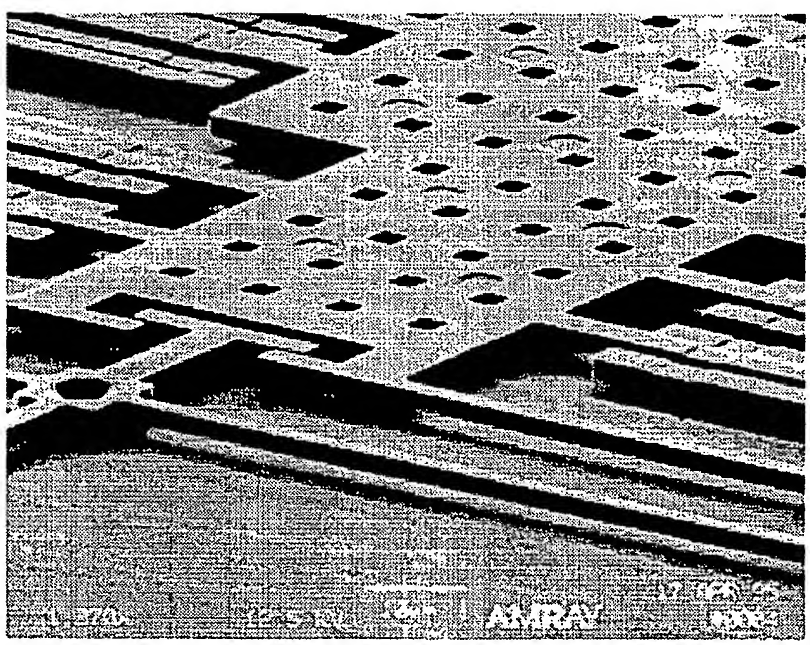


Fig. 2. SEM of the ADXL-05 surface micromachined accelerometer, showing the suspension and interdigitated sense and force-feedback electrodes (courtesy of Kevin H.-L. Chau, Analog Devices, Inc., Wilmington, MA, USA).

bearings have been an issue since the first demonstration of electrostatic micromotors in the 1980s [12]. In micromechanical optical modulators, suspended microstructures impact the substrate normally, i.e., without shear [13,14]. Other micromirror structures impact the substrate at an edge [4]. The large friction coefficients observed between polysilicon and itself and other thin films [15] have motivated investigation of organic coatings for lubrication [16].

Prior to discussing the various strategies for alleviating these tribological phenomena in surface micromachines, it is worthwhile to discuss the typical constraints imposed by the post-release assembly and packaging processes.

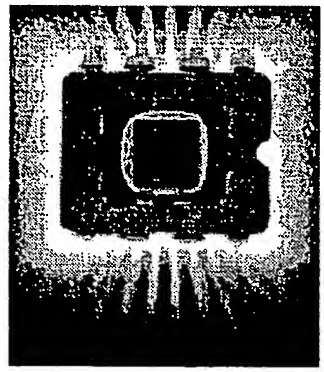


Fig. 4. Micrograph of the ADXL-76 accelerometer in its ceramic dual inline package (courtesy of Kevin H.-L. Chau, Analog Devices, Inc., Wilmington, MA, USA).

3. Back-end processes

A schematic outline of conventional wafer dicing, die attach and wire bonding, and hermetic encapsulation back-end steps is given in fig. 3. Particle generation during dicing and die handling must be kept to a minimum, since particles could contaminate the surface microstructure and wet cleaning processes are not desirable. A major consideration is the temperatures required for die attach and hermetic encapsulation. For a gold–silicon eutectic die attach, the package and chip are heated to around 360°C. Conducting epoxies need lower temperatures, but may outgas after encapsulation. Hermetic encapsulation can be achieved by several processes, such as soldering, with temperatures in the range of 350–425°C being typical. The final ambient in the package can be an inert gas or vacuum. Fig. 4 is a micrograph of a surface micromachined accelerometer in its ceramic dual inline package, prior to sealing the lid [9].

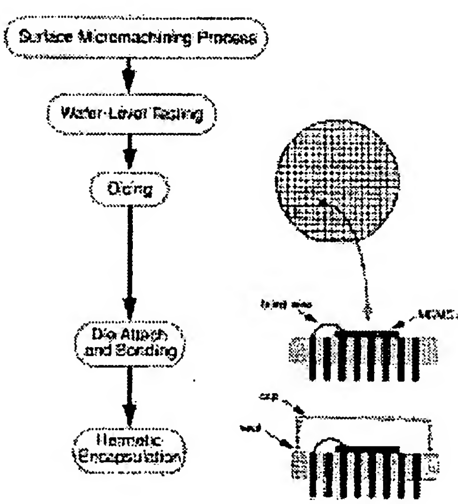


Fig. 3. Schematic diagram of conventional wafer dicing, die attach and wire bonding, and hermetic encapsulation steps.

Innovative MEMS packaging processes have been developed in order to simplify the back-end steps and reduce costs. In fig. 5, a polysilicon accelerometer is protected by a single crystal silicon micromachined cap, which enables it to be encapsulated in plastic, along with the adjacent CMOS signal detection and processing chip [17]. Polysilicon surface-micromachined shells can be transferred from a donor wafer to the MEMS wafer and sealed using a gold–silicon eutectic to achieve vacuum encapsulation [18]. In contrast to fig. 5, these polysilicon shells encapsulate only the immediate area of the microstructure.

A thin-film shell can also be fabricated by an extension of surface micromachining [19–21]. Ad additional sacrificial layer is deposited on the microstructure. After patterning this film, one or more structural films are deposited to form the shell and etch-access channels are opened at its perimeter. Following removal of the sacrificial layer, the access channels are sealed by another structural layer deposition, possibly preceded by an oxidation step. Fig. 6 is a SEM of an encapsulated polysilicon microresonator in which polysilicon and silicon nitride are used to form the microshell [19]. Sealing processes require temperatures of 600–900°C, far in excess of those needed for conventional encapsulation.

4. Eliminating release-related adhesion

Several engineering approaches to minimizing or eliminating release-related stiction have been demonstrated. Since capillary forces play a central role in collapsing the microstructure, an obvious "work-around" is to prevent formation of a meniscus. Freeze-drying [19,22] and supercritical CO_2 drying [23] have been successfully applied to surface micromachining. Another

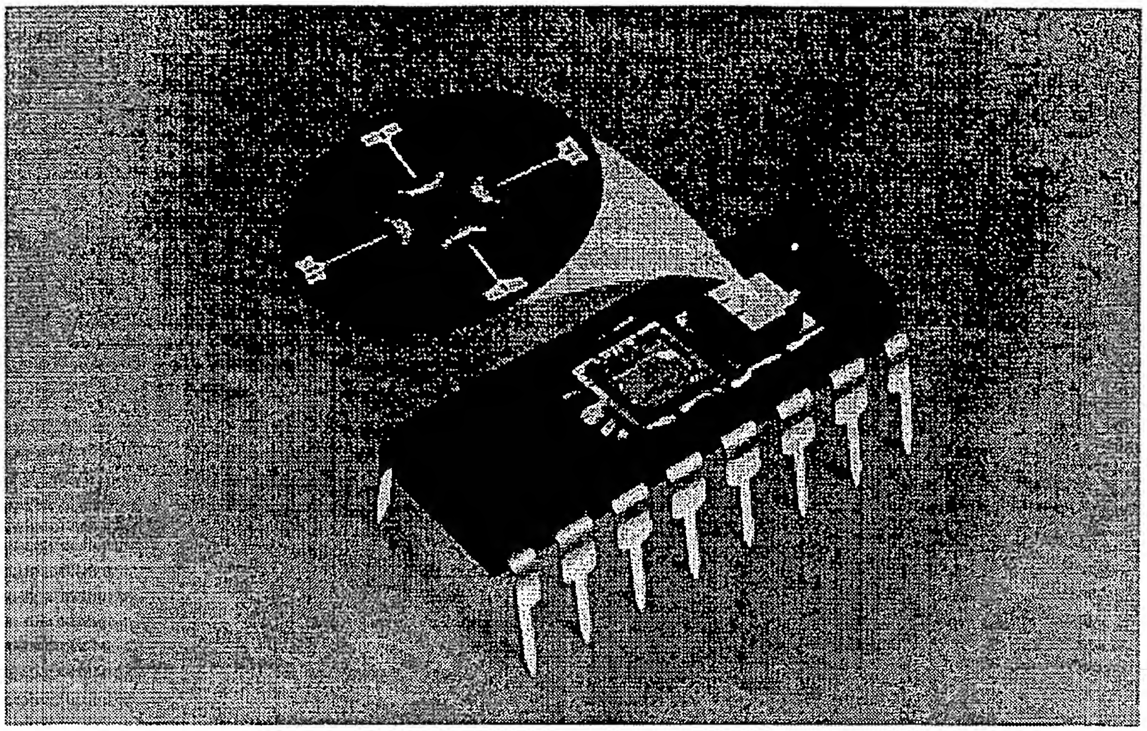


Fig. 5. Micrograph of the Motorola MMAS40G10D accelerometer prior to plastic injection molding. The inset shown is a SEM of the polysilicon sense element (courtesy of Raymond M. Roop and Carol T. Smith, Motorola Sensor Products Division, Phoenix, AX, USA).

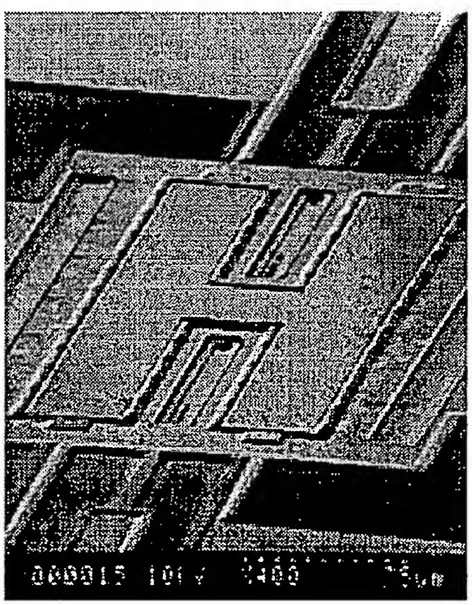


Fig. 6. SEM of a H-shaped encapsulated polysilicon microresonator (reprinted from ref. [19] with kind permission of Elsevier Science S.A., Lausanne).

approach is to perform a partial undercutting of the surface microstructure and fill the voids with a polymer layer. The polymer prevents collapse of the microstructure after completion of the sacrificial layer etch and can be removed using an oxygen plasma without need for immersion in a wet etchant [24].

An alternative approach is to make the surfaces of the polysilicon hydrophobic, by formation of a self-assembled monolayer (SAM) film [11,25]. The capillary attraction that collapses the microstructure when the surfaces are hydrophilic is not present for hydrophobic surfaces. As a result, highly compliant microstructures can be dried successfully by pulling the wafer directly from the final water rinse [25].

5. Strategies for minimizing post-release adhesion

Since release-related stiction is no longer a stumbling block to surface micromachining, recent research has focused on ensuring that adhesion does not occur during operation or handling of the packaged device. High reliability will require the development of processes that yield low surface energies for the microstructure and the adjacent surfaces, with minimal contact area also being desirable. It is worth noting that surface microstructures

should be designed to contact surfaces at the same potential, to avoid electrostatic attraction and potential contact welding. The accelerometer in fig. 2 is designed to impact the T-shaped limit stop (located on the left side of the SEM) before the interdigitated capacitor plates are shorted.

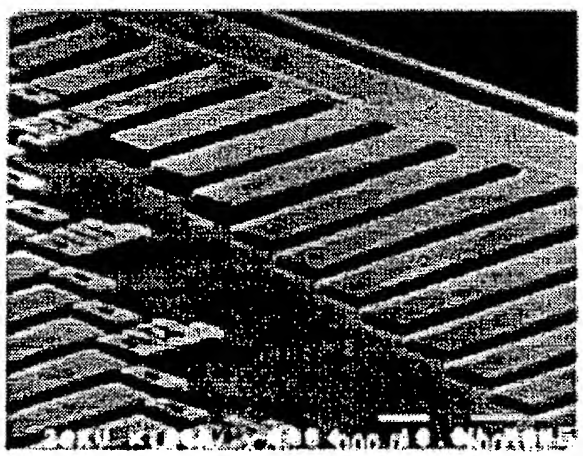
Post-release stiction of polysilicon microstructures can be quantified by means of an electrostatically actuated cantilever beam array [25,26]. The polysilicon beams are deflected electrostatically and contact an underlying polysilicon layer that is at the same electrical potential (fig. 7). After contact, beams shorter than the detachment length are sufficiently stiff to pull off the polysilicon layer, whereas longer beams remain adhered. The detachment length can be related to the work of adhesion between the contacting surfaces [27].

Polysilicon surfaces as deposited and annealed are rather rough, with rms values in the range of a few nanometers to a few tens of nanometers based on one study [28]. As such, additional surface roughening alone is found to have a limited effect on reducing adhesion [26,29,30]. In order to minimize the work of adhesion, it is desirable to form a hydrophobic surface on the polysilicon. Hydrogen-terminated silicon is extremely hydrophobic, as are SAM films. Hydrophilic polysilicon with a thin oxide passivation has a work of adhesion of 20 mJ/m^2, in comparison to 40 $\mu J/m^2$ for hydrogen-terminated (HF-treated) polysilicon [26] and 3 $\mu J/m^2$ for polysilicon coated with an octodecyltrichlorosilane-based SAM [25]. The detachment length is nearly 1 mm for a 2 μm thick, OTS-coated polysilicon cantilever suspended 2 μm above the polysilicon-coated surface. The fluorinated SAM coating based on perfluorooctoethyltrichlorosilane appears to yield an even longer detachment length, indicative of an even lower work of adhesion [31].

Integration of a process or coating for achieving a low adhesion energy surface is highly constrained, due to the thermal cycles used in the back-end process outlined in fig. 3. For example, it is convenient to form the SAM films after rinsing following the sacrificial layer etch, without allowing the wafer to dry. However, the hermetic sealing temperature and ambient may degrade the SAM. For the case of OTS-based SAM, its contact angle does not degrade after 30 min at 400°C in nitrogen; however, 150°C in air causes a marked reduction in contact angle [25]. Lower temperature hermetic sealing processes are under development for MEMS packaging [18], which would relax the demands on thermal stability of the anti-stiction coating.

Survival of the film through the back-end process

(a)



(b)

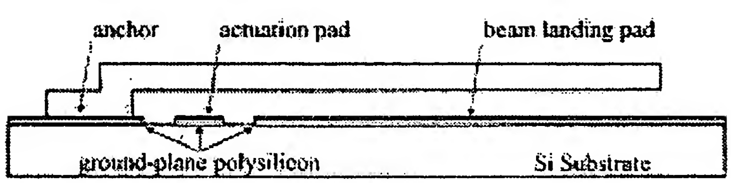


Fig. 7. (a) SEM of an electrostatically actuated cantilever beam array, and (b) a schematic side view of one of the beams.

is not the sole consideration in integrating a SAM into a surface micromachined device. Self-assembled monolayers may interfere with backside contacts to the MEMS chip and with wafer-level probing of metal pads, since they are insulating films. In addition, the presence of chlorine in the trichlorosilane head group raises concern of potential corrosion of the aluminum metallization on the MEMS chip. A final consideration is that the anti-stiction coating may degrade the mechanical performance of the sensor. For example, the internal damping of a resonating surface microstructure could be increased by the 20 Å thick monolayer organic coating on its upper and lower surfaces. Note that the total structural thickness is typically $2\ \mu m = 20\,000$ Å, which is only a factor of 500 greater than that of the total thickness of anti-stiction coating!

Thin-film microshells are formed and sealed using high-temperature processes such as oxidation and low-pressure chemical vapor deposition, which preclude the use of organic anti-stiction coatings. Amorphous or diamond-like carbon films are hydrophobic coatings [32,33] that could potentially survive to provide low adhesion inside a thin-film microshell. If coating of the entire structure is required, then these films would be deposited more than once during the microstructure fabrication. Residual stress in these films is a major concern, since it could cause warpage or buckling of the coated micromechanical structure.

Microactuators such as electrostatically actuated mirrors, lenses [34,35], and comb-driven mechanisms [36] have been demonstrated. These applications involve sliding surfaces and therefore, friction and wear. Beyond one study on the effects of SAM films on friction and wear in polysilicon electrostatic wobble motors [16], and another in digital micromirror devices [37], the subject remains open. In order to minimize wear, it is likely that hard, inorganic coatings (e.g., diamond-like carbon or refractory metals) will be called for.

6. Summary

In summary, many novel microsensors and microactuators have been realized recently by advances in fabrication techniques. In parallel, several surface treatments with various degrees of success have been identified for alleviating the problem of stiction in this technology. In order to be effective, the anti-stiction process must be incorporated into the highly constrained release, dicing, assembly, and packaging processes, with the latter step requiring elevated temperatures. Furthermore, the surface treatment must not degrade the electrical and mechanical performance of the microdevice. It seems unlikely that one treatment will satisfy all these applications. Rather a variety of coating technologies will be developed, each fine-tuned for a particular application. In addition, friction and wear are currently limiting the operation and lifetime of micromachines. It remains to be discovered how the various anti-stiction surface treatments, will affect friction coefficients and wear characteristics of micromachines.

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